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Transport through a 2DEG channel with superconducting boundaries

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Abstract

We have investigated transport through a channel with superconducting boundaries where electrons are confined by Andreev reflection. Superconducting phase-sensitive transport is discussed using qualitative arguments. The transfer resistance R_t through the channel as well as the resistance R_i between the injector and the channel have been measured as a function of the phase difference ϕ between the superconducting boundaries. It is not yet clear that the observed oscillation in resistance can be attributed to quasiparticle phase-sensitive transport. The oscillation amplitude in R_t due to the transmitted current modulation is less than 0.1% in this experiment.

Keywords: Electrical transport; Electrical transport measurements; Indium arsenide; Niobium; Quantum effects; Quantum wells; Semiconductor–superconductor interfaces; Superconductivity

1. Introduction

Recently, much attention has been devoted to superconducting phase-sensitive normal transport. The phase of the superconductor plays an important role in supercurrent flow in bulk superconductors as well as in Josephson junctions. An interference effect on the resistance, which is influenced by the superconducting phase difference, has been pointed out by Spivak et al. and Altshuler et al. [1]. Through the Andreev reflection (AR) process at the interface between a normal metal (N) and a superconductor (S), the phase of quasiparticles is shifted by the phase of superconducting order parameter. The basic idea is that if the superconducting phase difference is externally controlled, the resistance of the normal layer is affected by constructive and destructive interference of quasi-particles. Several types of interferometers have been proposed [2–6], and such phase-sensitive transport has been experimentally confirmed [7–10].

In this paper, we have studied transport through a two-dimensional electron gas (2DEG) channel with superconducting boundaries. The decay length of incoming electrons in the channel is sensitive to the phase difference between the super-

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conducting boundaries. The transfer resistances R_t through the channel, as well as the resistance between the injector and the channel R_i, have been measured as a function of the phase difference ϕ between the superconducting boundaries. It is not yet clear that the observed oscillation in resistance can be attributed to quasi-particle phase-sensitive transport. The oscillation amplitude in R_t due to the transmitted current modulation is less than 0.1% in this experiment.

2. Principle of operation

First we discuss the operation principle of the superconducting phase-sensitive transport in a channel with superconducting boundaries. The channel has the same structure as an SNS junction where N is the 2DEG. We consider the decay length ξ of the incoming electrons in the channel with parallel direction to the two superconducting boundaries.

The Andreev reflections between two superconducting boundaries form discrete energy levels (bound state $E_n(\phi)$) which carry supercurrent. $E_n(\phi)$ depends on the phase difference ϕ between the superconducting boundaries. In the limit where a channel width is shorter than the coherence length, one gets the simple result $E_n(\phi)=\Delta(1-T_P\sin^2(\phi/2))^{1/2}$ [11], where T_P is the transmission coefficient.

Recently, it has been pointed out [12] that the bound state leads to an effective energy gap Δ_{eff}. The effective energy gap is approximately given by $\Delta_{eff}=(1/4)T_{SIN}E_n(\phi)$, where T_{SIN} is the transparency at the SN interface. In analogy to the decay length of a quasi-particle in a superconductor, this effective energy gap leads to the relation $\xi=\hbar v_F/\Delta_{eff}=4\hbar v_F/T_{SIN}E_n(\phi)$. Therefore, the bound state formed between two superconducting boundaries gives the decay length of the incoming electrons.

The bound state has maxima at $\phi=2\pi n$, and minima at $\phi=(2n+1)\pi(n=0, 1, 2, \ldots)$. Using the expression of ξ, the transmitted current I_t which is expected to be proportional to $\exp(-L/\xi)$ shows minima at $\phi=2\pi n$ and maxima at $\phi=(2n+1)\pi$. Here L is the channel length. Therefore, we expect that we can modulate the transmission current through the channel by controlling ϕ.

3. Sample preparation

The structure of the sample is shown schematically in Fig. 1. A channel was made by surrounding an InAs 2DEG with two parallel superconducting Nb electrodes (E0). Because the receiver electrode (E2) has to be put close to the channel, all electrodes were made of Nb at the same time for alighment accuracy. The channel length L was 0.5 μm which is of the order of the expected decay length ξ. The width W was $\sim$0.2 μm. Electrons were injected from the 0.15 μm wide injector electrode (E1) to the channel. The transmitted electrons were detected by a receiver electrode (E2) which was placed inside the superconducting ring. The distances between the injector and the Nb electrode (E1–E0) and between the receiver and the Nb electrode (E2–E0) were 0.1 and 0.3 μm, respectively. To control the phase difference ϕ, a superconducting ring geometry was formed. The area S of the ring was $\sim$60 μm^2.

The 2DEG was formed in a 20 nm InAs layer of InAs/GaSb heterostructures. The carrier concentration and the electron mobility of the 2DEG InAs were $N_S=1.7\times10^{12}$ cm^{-2} and $\mu=30\,000$ cm^2/Vs. The carrier concentration gives a Fermi wavelength of 18 nm. The electron mean free path is estimated to be 0.65 μm from these values. Prior to deposition of Nb, the free surface of InAs was Ar-ion cleaned. The superconducting electrodes of 60 nm Nb were fabricated by standard

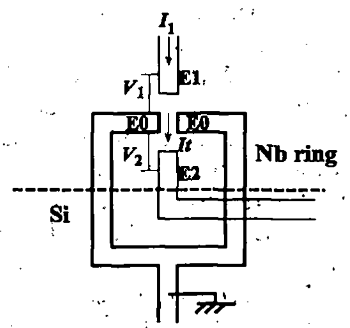

Fig. 1. Schematic structure of channel.

electron beam lithography and lift-off techniques. Si (100 nm thick) was used as an insulating layer between the superconducting ring and the lead for the receiver electrode.

4. Results and discussion

Both voltages V_1 between E1 and E0 and V_2 between E2 and E0 were measured at $T=50$ mK by supplying currents I_1(E1–E0) and I_2(E2–E0) independently. E0 was always grounded to eliminate the leakage current through the 2DEG underneath Nb ring electrodes. The resistance from the injector to the ring $R_i = dV_1/dI_1$ was 16 Ω, and the resistance from the receiver to the ring $R_r = dV_2/dI_2$ was 41.5 Ω. On supplying I_1 from E1 to E0, V_2 is a measure of the number of electrons transmitted through the channel. The transfer resistance $R_t = dV_2/dI_1$ was 1.6 Ω. In another sample, R_t was only 0.01 Ω; this was achieved by putting the receiver electrode 1 μm away from the channel. This result suggests that electrons through the channel do not reach the receiver electrode ballistically, and that the 2DEG became diffusive by the fabrication process.

A sharp dip structure was observed in $dV_1/dI_1 - I_1$ characteristics below $I_1 = 1$ μA, but dV_1/dI_1 did not reach zero. This dip is attributed to the supercurrent, which is estimated to be 0.5 μA. The dip structure was not observed in $dV_2/dI_2 - I_2$ because the Josephson coupling between the Nb ring and receiver electrode was weak.

$R_t = dV_2/dI_1$, which is proportional to the transmitted current, was measured as a function of the magnetic field B for different DC current biases I_{DC}. The phase difference ϕ can be controlled by the relation $\phi = 2\pi(BS/\Phi_0)$, where Φ_0 is a flux quantum ($=h/2e$). The results are shown in Fig. 2. For $I_{DC}=0$, oscillations in the resistance R_p were observed with a period of about 0.35 G. This magnetic field corresponds to a flux quantum Φ_0 through the Nb ring area. The oscillations exhibit resistance minima at $BS = n\Phi_0$ ($\phi = 2\pi$n). This is because the Josephson coupling between E1 and the ring leads to a DC–SQUID oscillation [7]. A DC bias current higher than the critical current

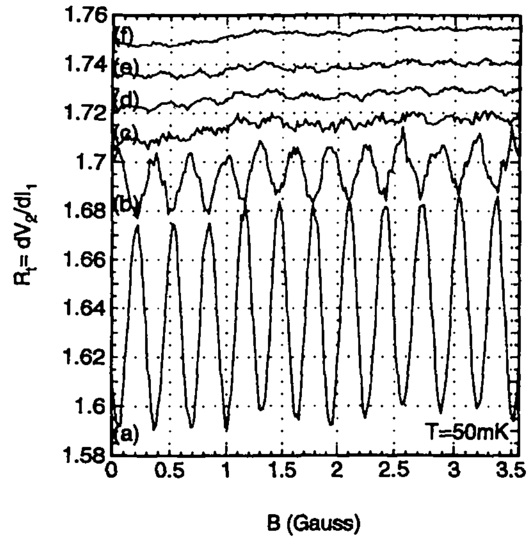

Fig. 2. Transfer resistance $R_t = dV_2/dI_1$ as a function of magnetic field for different DC biases I_{DC}. I_{DC} = (a) 0, (b) 3, (c) 10, (d) 15, (e) 20, and (f) 40 μA.

was added between the injector electrode and the Nb ring in order to suppress the Josephson coupling. A shift in oscillation phase and a reduction in amplitude were observed. The resistance with $I_{DC} = 3$ μA showed maxima at $\phi = 2\pi n$. The transfer resistance R_t with $I_{DC} = 10$ μA showed minima again at $\phi = 2\pi n$, and a gradual shift in phase was observed by increasing I_{DC}. Under a high DC bias condition with $I_{DC} > 30$ μA, the resistance again showed maxima at $\phi = 2\pi n$. This behavior cannot be explained by the operation principle because the transmitted current has minima at $\phi = 2\pi n$. Therefore, the transfer resistance R_t should have minima at $\phi = 2\pi n$.

In comparison, the resistance $R_i = dV_1/dI_1$ was also measured for different DC current biases. This is the same measurement configuration as used for the quasi-particle interferometer [7]. Resistance maxima at $\phi = 2\pi n$ were observed under the high bias current condition. Fig. 3 shows a comparison in oscillation amplitude as a function of DC bias current. In this plot, the phase of the oscillation is not taken into account. The dashed line is the calculated oscillation amplitude expected from the DC–SQUID coupling. Under high bias conditions, the oscillation amplitude of the resistances is higher

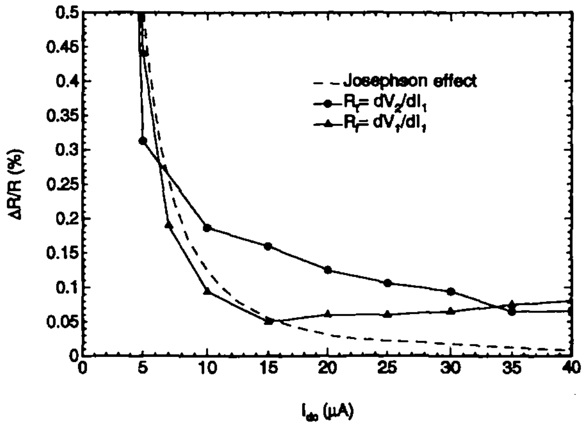

Fig. 3. Comparison of the oscillation amplitude in resistance as a function of I_{DC}.

than expected from the DC–SQUID coupling. However, the resistance maxima at $\phi = 2\pi n$ cannot be explained by the operation principle nor by interferometer operation. The oscillation amplitude in R_t due to the decay length modulation is less than 0.1% in this experiment.

In Section 3, we assumed a ballistic channel and a well-defined bound state. After the fabrication process, it is observed that the carrier concentration of the InAs underneath the Nb electrodes is enhanced, and the electron mobility is much reduced [13]. This gives a mean free path of 10 nm. It is not so clear how the principle of operation will hold under these interface conditions.

5. Conclusion

We have proposed an operation principle of superconducting phase-sensitive transport in a 2DEG channel surrounded by superconducting boundaries. The oscillation amplitude in R_t due to the decay length modulation is less than 0.1% in this experiment. It would be necessary to measure the sample with normal injector and receiver electrodes to eliminate the DC–SQUID oscillation.

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